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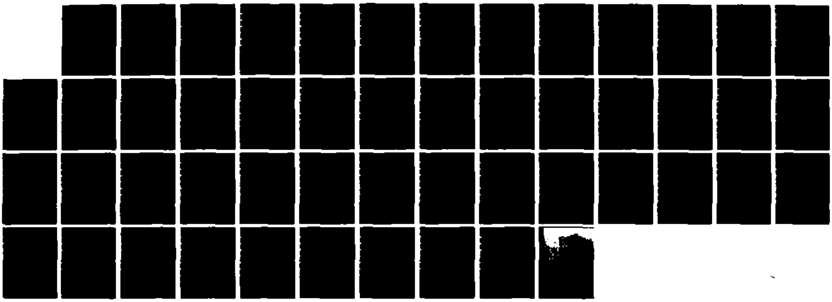

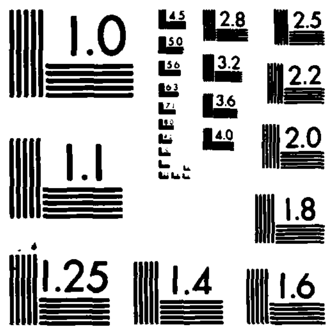

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LITERATURE REVIEW OF SPACECRAFT CHARGING

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JAYCOR
P.O. Box 85154
San Diego, CA 92138

Scientific Report No. 1

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AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
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A literature review has been performed on spacecraft electrical anomalies, arc discharges on spacecraft and laboratory simulations of spacecraft materials, and measurements of electrical transients on spacecraft. Analyses in the literature of the probable causes of the observed anomalies are summarized along with the data on measured electrical transients on operating spacecraft. An arc type is tentatively selected for further laboratory investigations of its radiated RF and other characteristics. A brief description of the proposed test plan is given.

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1. INTRODUCTION

Arc discharges between differentially charged portions of orbiting satellites have been the subject of considerable speculation and study for over ten years. This interest in satellite arc discharges is not just an idle curiosity since there is evidence that such discharges may have been the cause of at least one catastrophic satellite failure and numerous other anomalous malfunctions of satellite electronic systems (Ref. 1).

The basic processes by which arc discharges occur are fairly well understood in general. The high-energy electrons in the space plasma impinge on the satellite and drive it to a potential that is determined by a balance between the incoming flux of electrons and an outgoing flux of secondary and photoemitted electrons. Because satellites invariably have some dielectric and some conducting surfaces, differential potentials can be developed between different parts of the satellite. If the energy spectrum and flux of plasma electrons is such that these differential potentials can reach some critical value, an arc discharge will occur. The resulting electromagnetic (EM) fields and charge then couple into the conducting structure and the electrical system of the satellite.

In spite of the above general understanding of arc discharges, there are still many puzzling details about the discharge process. For example, it is not known for sure just where and how an arc is initiated on a satellite; how an arc propagates from its initiation point across the charged dielectric surface; what fraction of the satellite surface will discharge in one event; the nature of the discharge (flashover, punchthrough, blowoff, or some combination of these)*; and the degree of coupling of a discharge into the satellite electronics system. In an attempt to provide answers to some of these questions, a research satellite (SCATHA) was launched in 1979, and one of its primary objectives was to make direct measurements of discharges that occurred on the satellite for correlation with other related measurements, such as the flux and energy of the incoming plasma electrons and the differential and total potential of the satellite to the ambient plasma at the time of the discharges. The data obtained thusfar from SCATHA have provided much useful and interesting information regarding the occurrence of arc discharges. However,

* The types of discharges are discussed in Section 2.

one of the difficulties with the systems used on SCATHA to detect arc discharges is that they also respond to some normal satellite electrical functions. Consequently, an unambiguous determination that an observed transient signal was the result of an arc discharge requires a tedious, delayed cross-correlation of the transient signal and numerous system electrical commands. Moreover, even when all known system impulses are eliminated as the cause of a particular transient, there is always the possibility that some unrecorded system impulse could have been the cause of the transient response.

The ultimate purpose of the program presently being performed by JAYCOR for the Air Force Geophysics Laboratory is to develop an on-board system that can unambiguously determine in real time when an arc discharge has occurred on a satellite. The first step in this program is a review of the available literature on arc discharges on both satellites and laboratory simulations of satellite-like structures. The purpose of this review is to attempt to identify the types of discharges that occurred, or are suspected to have occurred, on spacecraft; which are likely to be significant for the disruption of spacecraft operations; and what are the electrical characteristics of the discharges which might be useful for the present program for discriminating between arc discharges and system noise.

The approach that has been used in this review is to first assemble all of the available data on spacecraft electrical anomalies, the direct measurements of electrical transients on satellites, and any analyses of the probable causes of these anomalies and transients. The satellites considered include both operational and research vehicles. The anomalies, transients, and some analyses of the probable causes of the anomalies are summarized herein for convenient reference. Although the satellite environments and the charging-up processes that lead to discharges are important and interesting questions in themselves, they were not deemed to be within the scope of the present effort. Hence they are not addressed in this review except to the extent that they are relevant to explaining specific transient responses.

Guided by the data on spacecraft potentials and environments at the time of the discharges, we have also reviewed the laboratory data on discharges in simulated spacecraft structures which appear most representative of the types of discharges that occur on satellites. Based on a comparison of these laboratory and satellite results, a determination is made of the type of discharge that is apt to have occurred most often on satellites and to have the most significant deleterious effects on satellite operations. This type of discharge is the logical candidate for further study in the remainder of this program.

To provide a background for the discussions and evaluations in the remainder of this review, Section 2 of this report presents a discussion of the possible arc discharge types. Section 3 lists the major sources of information that were consulted for this review, including personal contact with some investigators. A bibliography of the most relevant papers for the present investigation is given in Appendix A. Section 4 contains a summary and analysis of the data on discharges for operational and research satellites and a discussion of similar laboratory simulations. In Section 5, various possible on-board and laboratory measurement techniques for detecting and identifying arc discharges on the exterior of satellites are listed and critiqued. In Section 6, the arc discharge type which JAYCOR proposes to study in the remainder of this program is identified and a brief program plan for the laboratory experiments is outlined.

2. CHARACTERISTICS OF ARC DISCHARGES

When the subject of arc discharges on spacecraft first arose, there was a tendency to think of the discharges occurring between differentially charged metallic objects. However, on spacecraft, deliberate attempts are now made to connnect all metallic sections of the structure to a common ground to avoid such differential voltages. Thus, metal-to-metal discharges should not be a problem on most spacecraft, except possibly betwen small isolated metalizations and lands inside electronic boxes. Such internal discharges are not the concern of the present investigation.

Since metal-to-metal discharges are not likely to occur on the exterior of a satellite, it is safe to conclude that all exterior discharges involve the release of charge that had been trapped in an exterior dielectric. It is possible that discharges could occur between two dielectrics. However, it appears much more probable that discharges occur between a charged dielectric and a nearby grounded conductor, for the following reasons. Since charge is free to move about in a conductor, it can adjust itself in response to the charge being deposited in a nearby dielectric to cause field concentration points which could initiate the discharges. Moveover, once a discharge is initiated at such a field concentration point, charge will flow from the dielectric toward that point in an attempt to relieve the field concentration. However, when the charge from the dielectric reaches the metal, it can flow away rather than collect to relieve the concentration, so the discharge current can continue for a longer time. Thus, in the remainder of this discussion, it is assumed that the important exterior discharges on a satellite involve discharge from a dielectric to a nearby grounded metal. Such dielectric-to-metal discharges are certainly plausible on spacecraft because practically every exterior dielectric of any significant size on a spacecraft is relatively thin and has a grounded substrate, such as the thermal blankets, cover glasses for the solar arrays, second surface mirrors, and optical solar reflectors.

Within the general category of dielectric-to-metal discharges, there are three discharge processes that have been observed in laboratory tests or postulated by investigators, namely, punchthrough, flashover, and blowoff.

Punchthrough is the process by which a discharge is initiated from a layer of charge deposited near the surface of a thin dielectric, through the bulk of the dielectric to its conducting substrate. Such discharges have been produced in the laboratory by many investigators when the edges of the dielectric samples are shielded from the incident electron beam. The threshold potential for such discharges are in reasonable agreement with the bulk breakdown of the dielectric, at fields on the order of 10^6 V/cm (Ref. 2).

At first glance, it might appear that a punchthrough breakdown would just involve the collapse of an electric dipole sheet consisting of the trapped electrons near the dielectric surface and the corresponding positive image charges in the conducting substrate. If this collapse of the dipole sheet was all that occurred in a punchthrough breakdown, the resulting electromagnetic fields that would appear outside the dielectric would be relatively small because the typical thicknesses for spacecraft dielectrics keep this dipole moment small. Moreover, the sign of the resulting structural return currents would be opposite to what is observed experimentally. However, it is known experimentally that punchthrough breakdowns are always accompanied by the blowoff of electrons, and perhaps positive ions and neutral particles, outward from the surface of the dielectric, that is, opposite in direction to the punchthrough current. There is disagreement in the scientific community on the physical mechanism that causes this blowoff, but that is not of particular concern for the present discussion. The important thing is that the electrons that blow off from the surface can travel distances that are much greater than the thickness of the dielectric. Thus, the dipole moment due to the motion of the blowoff electrons can be orders of magnitude larger than the dipole moment of the original charge sheet and its image in the substrate. It is this large dipole moment that is primarily responsible for the large radiated fields and return electrical currents that accompany a punchthrough discharge.

Flashover is defined here as the release of charge from the surface of a dielectric to a nearby conductor, which is usually electrically connected to the conducting substrate of the dielectric. It is not clear whether the lateral motion of the trapped electrons across the surface of the dielectric occurs through the bulk of the dielectric, as in a Lichtenburg figure, or by an electron cloud exterior to the dielectric, or possibly both under different circumstances. For present purposes, this distinction is not important. Flashover discharges can be generated in the laboratory by exposing the edge of a dielectric on a conducting substrate to the incident electrons. The threshold potential for initiation of a flashover discharge is usually less than the threshold for the initiation of a punchthrough (Ref. 3). The initiation process is probably an enhanced electric field near the edge of the dielectric (Ref. 4). The physical damage that has been observed near the edge-ring of laboratory samples (Ref. 5) is evidence that the flashover process often is concentrated in those regions.

Similar to a punchthrough, if a flashover discharge only involved charge moving along the surface of the dielectric to the adjacent conductor and thence back to the substrate of the dielectric, the magnitude of the radiated fields and the return currents would be quite small, and the return current would be opposite in sign to what is observed, because the driving mechanism would again be just the collapse of a small dipole moment. However, again similar to a punchthrough, a flashover is accompanied by a blowoff of electrons, and perhaps ions and neutral particles. The large dipole moment due to the blowoff electrons is the primary driving mechanism for the large radiated fields and return current that accompany a flashover discharge.

It has been observed that both types of discharge can result in physical damage to the dielectric. Excellent photographs of surface discharge due to flashover discharges are given in Reference 5. Examples of physical damage due to punchthrough discharges are the well known "tall" formations in thick dielectric that have been irradiated with high-energy electrons.

Meulenberg (Ref. 6) has proposed a mechanism by which a blowoff discharge can occur independent of flashover or punchthrough. However, there is serious doubt in the scientific community whether such isolated blowoffs actually occur. Basically, there is no conclusive evidence that an isolated blowoff discharge has ever been observed whereas, as discussed above, there is a large body of evidence that flashover and punchthrough discharges do occur and are always accompanied by blowoff of charge. Thus, it is JAYCOR's opinion that blowoff may not be an independent discharge process but is a result of flashover or punchthrough.

3. DATA SOURCES

The main source of information for electrical anomalies on operational satellites was the dossier compiled by the Aerospace Corporation. These data were made available to JAYCOR in three forms, (1) preliminary summaries of anomalies for DoD satellites DMSP, DSP, DSCS II, FLTSATCOM, and NATO III, (2) a computer printout of all anomalies recorded in the Aerospace Orbital Data Anlysis Program (ODAP) through August 1983, and (3) an Aerospace correlation analysis of these data as of March 1980. Typical pages from the preliminary summaries and the ODAP printout are reproduced as Figures 1 and 2. The 1980 Aerospace analysis is particularly interesting because the authors have correlated the occurence of about half the electrical anomalies with the occurrence of magnetic storms, solar flares, and/or deep-space protons. Two other analyses of these data were given References 1 and 7.

Information about discharges measured on SCATHA, on a 1973 geosynchronous satellite that carried a transient pulse monitor (TPM), and on a Canadian-American Communications Technology Satellite (CTS) that carried a transient event counter (TEC) was obtained mainly from the summaries of the three Spacecraft Charging Conferences (Refs. 8, 9, and 10), several NASA technical memoranda, the Journal of Spacecraft and Rockets (1976 to present), the IEEE proceedings of the Nuclear and Space Radiation Effects Conference (December issues, 1975 to present), and several miscellaneous papers and reports from Aerospace, TRW, Stanford Research Institute, and IRT.

On September 2, 1983, a trip was made to Los Angeles to discuss both the ODAP and SCATHA data with Messrs. Robert Broussard, Jay P. Leary, Robert Pruett, Harry Koons, and Al Vampola. Mr. Paul Mizera was unavailable during that visit. In addition to discussing the ODAP and SCATHA data, we obtained the latest copies of the ODAP computer data and preprints of presentations on SCATHA data.

EVENT NO.	S/C	DATE	TIME	STATE	TDAL CHANNEL				BEACON		RESOLVER SELECT LOGIC	REMARKS
					EE	NE	NN	EN	EC	NC		
11	9433	1-19	1726	BEFORE AFTER	+4 +4	-4 -4	-4 -4	-4 +12	- -	- -	- -	AZ-1 MOTOR STEP CHANGE
12	9434	1-26	1023	BEFORE AFTER	-4 -12	-4 -4	-4 -12	-4 +4	-12 0	- -	EL-2 AZ-1	MUX. LOST SYNC
13	9433	1-27	0705	BEFORE AFTER	0 0	-4 -4	-4 +12	-4 +12	- -	- -	- -	AZ-1 AND EL-2 MOTOR STEP CHANGES
14	9434	1-30	0745	BEFORE AFTER	0 +12	+4 -12	+4 -12	+4 -4	- -	-10 MAX	EL-2 EL-1	MUX. LOST SYNC
15	9433	2-1	0757	BEFORE AFTER	0 0	-4 -4	+4 +12	+4 +12	- -	- -	- -	AZ-2 AND EL-2 MOTOR STEP CHANGES
16	9433	2-12	0957	BEFORE AFTER	0 0	-4 -4	+4 +12	+4 +12	- -	- -	- -	EL-1 MOTOR STEP CHANGE
17	9433	2-17	0935	BEFORE AFTER	0 0	-4 -4	+4 +12	+4 +12	- -	- -	- -	EL-2 MOTOR STEP CHANGE

Figure 1. Typical page from preliminary summaries of anomalies

```
INCIDENT      11          PROGRAM -DSCS 2        FLIGHT NO. -01            LAUNCH DATE-71 NOV
  SUBSYSTEM       -GUIDANCE AND CONTROL SUBSYSTEM
  ASSEMBLY            -DESPIN ELECTRONICS ASSEMBLY
  SUBASSEMBLY OR TYPE-CONTROL TIMING ASSEMBLY
  MODULE OR TYPE      -
  CAUSE           -DEEP SPACE ION
  FAILURE TIME -  4       MANUFACT-TRW           DUTY CYCLE -100           CLASS      -ELECTRICAL
  REPORT NO.   :1-11      FEEDBACK-ANOMALIES     CRITICALITY-DEGRA PERF    ORITAL PHASE-STEADY ST
               ***   SYMPTOM - POINTING ERROR OF NC-1 ANTENNA                                 ***
               ***   CAUSE - CONTROL TIMING ASSEMBLY/DESPIN ELECTRICAL ASSEMBLY REGISTER      ***
               ***     SCRAMBLE OCCURRED WHICH BIASED THE DESPIN PLATFORM BUT DID NOT         ***
               ***     CHANGE THE DESPIN MODE FROM NORMAL, PROBABLY PROTON HIT                ***
               ***   RECOVERY METHOD - POINTING LATER CORRECTED BY COMMANDING PROPER BIAS     ***
               ***   CORRECTIVE ACTION - GROUNDED ALL (WHERE POSSIBLE) EXTERNAL CONDUCTIVE    ***
               ***     SURFACES TO ELIMINATE DIFFERENTIAL CHARGING DURING SUBSTORM            ***

INCIDENT      16          PROGRAM -DSCS 2        FLIGHT NO. -01            LAUNCH DATE-71 NOV
  SUBSYSTEM       -GUIDANCE AND CONTROL SUBSYSTEM
  ASSEMBLY            -DESPIN ELECTRONICS ASSEMBLY
  SUBASSEMBLY OR TYPE-CONTROL TIMING ASSEMBLY
  MODULE OR TYPE      -
  CAUSE           -DESIGN,MAGNETIC STORM
  FAILURE TIME - 11       MANUFACT-TRW           DUTY CYCLE -100           CLASS      -ELECTRICAL
  REPORT NO.   :1-16      FEEDBACK-ANOMALIES     CRITICALITY-TEMPORARY     ORITAL PHASE-STEADY ST
               ***   SYMPTOM - DESPIN CONTROLLER LOST NORMAL MODE EARTH LOCK                  ***
               ***   CAUSE - COMMAND SCRAMBLE RESULTED IN DESPIN CONTROLLER PARAMETERS        ***
               ***     BEING CHANGED                                                          ***
               ***   RECOVERY METHOD - GROUND STATION ISSUED COMMAND WHICH RESULTED IN        ***
               ***     SUBSEQUENT ESTABLISHMENT OF RATE MODE DESPIN CONTROL                   ***
               ***   CORRECTIVE ACTION - ADDED CIRCUITRY TO ELECTRICAL INTEGRATION            ***
               ***     ASSEMBLY AND SWITCHING LOGIC ASSEMBLY TO AVOID SIMULTANEOUS COMMAND    ***
               ***     EXECUTE DURING CONVERTER OVERLOAD, INCORPORATED WIRING AND             ***
               ***     COMPONENT CHANGES IN RESET GENERATOR ASSEMBLY TO MAKE IT               ***
               ***     INSENSITIVE TO MAGNETIC SUBSTORMS                                      ***
```

Figure 2. Typical page from ODAP printout

4. SUMMARY/ANALYSIS OF DISCHARGE DATA

This section is divided into discussions of (1) anomalies observed on orbiting sate (2) measured discharges on satellites, and (3) laboratory experiments on discharg electrical noise.

4.1 SATELLITE ANOMALIES

At least three different analyses have been performed on portions of the elec anomalies that have been detected on operational satellites (Refs. 1, 7, and an in Aerospace memorandum). The types of anomalies have included (1) uncomm switching of solid-state logic circuitry, primarily in a tunnel diode amplifier limiter catastrophic loss of power to a despun platform, (3) erroneous commands and logic which have led to unintended spinup of despun platforms, and (4) abnormal operat switching logic assemblies. All three analyses of these data have indicated statistical correlation between the observed anomalies and periods of inc magnetopheric substorm activities, solar flares, and/or galactic particles, even t reliable data on the space environment in the vicinity of the satellites immediatel to and during the anomalies was usually not available.

Reference 1 is a study of the anomalies observed on four DSCS II satellites November 1971 to October 1974. The dates of the anomalies during this period compared to any available data on magnetospheric activity, including data from altitude geophysical stations and the DMSP satellite auroral photographs. The auth Reference 1 state that "magnetospheric substorm activity is associated with 90% logic reset anomalies, with all nine of the converter switching anomalies, and two three of the spinup anomalies." However, they caution that magnetospheric sub occur far more frequently than anomalies, so a conclusive determination magnetospheric substorms are responsible for the anomalies will require identification of the plasma environment around the satellites.

Reference 7 attempts to correlate the same DSCS II anomalies with the geomagnetic activity index at Anchorage, Alaska and the midnight-to-dawn sector of the local satellite time when the temperature of the plasma electrons is usually relatively large. The spinup anomalies occurred in the midnight-to-dawn sector, coincident with the occurrence of large magnetic storms. However, the other anomalies did not correlate as well with either the midnight-to-dawn sector or the magnetic activity index. Possible reasons which the authors of Reference 7 suggested for this lack of correlation were (1) some anomalies may not be of environmental origin, (2) some environmental phenomenon other than a substorm event may be the cause of the anomalies, and (3) there may be a delay between the charge-up phase of a discharge (presumably during the midnight-to-dawn sector) and the occurrence of the discharge, for example, due to a sudden illumination of a portion of the satellite later in the day. To these can be added two more possible reasons, (4) the magnetic activity index at one location on the earth's surface may not be a reliable measure of the environment experienced by the satellite and (5) some of the discharges may occur deep inside the satellite where the charging up occurs over a relatively long period of time due to the high-energy tail of the space spectrum, and the discharges could then occur almost randomly in time.

In the Aerospace analysis, the authors attempt to correlate the electrical anomalies on file in the ODAP program as of March 1980 for six satellites (DSCS II, DSP, NATO-III, DMSP, GPS, and FLTSATCOM) with magnetic storm, solar flares, and galactic particles. The magnetic storm activity was based on the Kp index (geomagnetic planetary three-hour index). The authors selected criteria for the critical-intensity thresholds for each type of activity and the time after an environmental event during which a significant effect on the satellite system is assumed to occur. They admit that their criteria are somewhat subjective and arbitrary. The selected thresholds are $Kp > 5$, solar proton fluences $> 10^7$ protons/cm^2 ($E > 30$ MeV), and fluxes of galactic heavy ions > 3 to 4/cm^2-s with energies up to several MeV. The assumed time windows during which magnetic storms with $Kp = 6$, 7, 8, and 9 would affect the electrical components were zero to 3, 7, 14, and 28 days respectively, and, for solar flares, zero to 6 days. In other words, if an anomaly occurred within 28 days after a magnetic storm with $Kp = 9$, the anomaly and the storm were assumed to be correlated. Based on this analysis, it was concluded that 9 different types of gliches that occurred repetitively on four different satellites were correlated with magnetic storms but four other repetitive gliches were not correlated with environmental events. A few anomalies appeared to be due to electrical spikes caused by solar flare proton fluxes and passage through the South Atlantic anomaly of the Van Allen belt, single event upsets due to high-energy particles, and total dose effects. None of these three causes of anomalies are of concern for the present study of electrical discharge effects. However, any anomaly that might be attributable to magnetic storms, such as the gain loss on the DSCS II tunnel diode amplifier, could be due to electrical transients caused by dielectric discharges.

In summary, although it is virtually impossible to conclusively determine that any specific anomaly or class of anomalies are due to dielectric discharge on satellites, the statistical correlation between many anomalies and magnetospheric substorms and the midnight-to-dawn sector of the satellite local time give strong evidence that dielectric discharges are responsible for at least some of these anomalies.

4.2 MEASURED SATELLITE DISCHARGES

Our literature review has identifed three satellites that carried instruments specifically to measure electrical discharges (or at least the transient electrical signals that result from the discharges), namely, SCATHA, an unidentified 1973 geosynchronous satellite, and a Canadian-American Communications Technology satellite (CTS).

SCATHA had two separate systems for measuring transient signals, a Transient Pulse Monitor (TPM) and a Charging Electrical Effects Analyzer (CEEA). The TPM (Ref. 11) received continuous electrical signals from four sensors, (1) a specially installed wire that ran parallel to and outside the foil wrap of the main vehicle wiring harness half way around the vehicle center tube, which was terminated in a low impedance; (2) another specially installed wire parallel to (1) but terminated in a high impedance; (3) a current probe on a regular circuitry wire from the solar array to the power conditioning unit (PCU), and (4) a current probe on one of the seven ground wires from the PCU to the satellite frame. The two current sensors (Nos. 3 and 4) are inside the main Faraday cage of the satellite. The two wires (Nos. 1 and 2) are outside the main Faraday cage but are inside the center tube that is open at only one end. The TPM gives the peak positive and negative signal during each second of operation, the integral of the signal over the one second interval, and the number of times the signal exceeds a preset threshold during the one second. However, if this threshold is exceeded more than once in any 1 μs period, it is counted only once. The results from these sensors are discussed later.

The CEEA (Ref. 2) actually consists of three instruments, a Very Low Frequency (VLF) Analyzer, a Radio Frequency (RF) Analyzer, and a Pulser Analyzer. The VLF Analyzer received signals from an exterior air-core loop antenna for the magnetic component of the fields and from a 100-m tip-to-tip dipole antenna for the electric fields. The RF analyzer received signals from two antennas, a 100-m tip-to-tip antenna and a 1.5-m monopole antenna along a boom perpendicular to the spin axis of the vehicle. Part of the functions of these two frequency analyzers was to detect external discharges and to frequency-analyze their electrical signatures. Essentially no information has been found in the literature on discharge data obtained with these two systems. In response to a specific question on the subject, Harry Koons indicated that little of the data from these devices has been analyzed for discharge pulses because the Pulse Analyzer gave much better information on transient pulses. Hence, these two frequency analyzers will not be considered further here.

The Pulse Analyzer (Ref. 12) monitors four sensors cyclicly for 16 seconds each at preselected time intervals. The four sensors are (1) a loop antenna around one of the two redundant space vehicle command distribution units, (2) a wire along the outside of a "typical" space vehicle cable bundle, (3) an external short dipole antenna at the end of a 2-m boom, and (4) a digital command line from the command distribution unit to the Pulse Shape Analyzer. Only sensor (3), the dipole antenna is external to the spacecraft Faraday cage.

SCATHA also carries 12 Satellite Surface Potential Monitors (SSPM) (Ref. 13) to measure the potential of the spacecraft relative to the ambient plasma and the differential potentials between several different material samples on the exterior of the satellite and spacecraft ground. These data are useful for determining the conditions that prevailed on and around the spacecraft at the time discharge events occurred. However, their response times are too slow (voltages are averaged for 0.25 sec) for them to be used to detect discharges or sudden changes in potential.

The discharge-monitoring [illegible]em (Ref. 14) that was carried on the 1973 geosynchronous satellite consist[illegible]vo metallic plates flush-mounted on the exterior surface of the satellite in the [illegible]ds[illegible]optical solar reflectors (OSR) (Ref. 11). It was biased to -5.6 V and was instru[illegible]ted to measure current flow between the plate and spacecraft ground. In the absence of a discharge, a small DC current would be measured, depending on the net incident/emission current density from the plates compared to the current density from the remainder of the spacecraft. When a discharge occurred, the instrument detected voltage pulses on the detector plate caused by the electromagnetic radiation (electric field normal to the satellite surface) caused by the discharge. This electric field is probably primarily due to the blowoff electrons that accompany arc discharges (see Section 2). The current of electrons returning to the plate should also increase due to the cloud of blowoff electrons. Laboratory calibrations indicated that that particular instrument could detect discharges that occurred up to 1 m from the detector (Ref. 14) but that range is undoubtedly a function of the strength of the discharge.

The Transient Event Counter (TEC) on the CTS (Ref. 15) counted the transient signals greater than 5 V on three wires that ran adjacent to the spacecraft wire harness at three locations within the spacecraft, (1) the attitude control harness, (2) the solar array instrumentation harness, and (3) the solar array power harness. There was a 5 μ s delay after a discharge pulse was counted to prevent counting line ringing as separate discharge pulses.

4.2.1 Data from SCATHA TPM

All four of the sensors in the SCATHA TPM system recorded numerous transient pulses every day, most of which were caused by normal operation of the spacecraft electrical system. The scientists on the project indicated (Ref. 16) that they were able to unambiguously identify and eliminate the pulses on the high- and low-impedance wires (sensors (1) and (2) described in Section 4.2) which were caused by normal system operation, but they could not devise a similar unambiguous system for the other two sensors. The pulses on sensors (1) and (2) that were not identified as internally-generated pulses always occurred on both sensors simultaneously, which is not surprising since these sensors are located close to the same cable bundle. These pulses were always electrically bipolar, which the scientists assert could not have been caused by any identifiable internal transient. Hence, they concluded that these pulses were the result of electrostatic discharges on the spacecraft.

After 177 days of operation, there were 189 signals which the scientists attributed to discharges, although none were definitely correlated with identifiable discharges (Ref. 16). Although this averages out to about 1 discharge per day, there were two days where 21 and 19 discharges were observed. All 189 discharges were observed on both wire sensors. Only 5 were observed on the ground wire and none on the solar array wire. Since there were many more TPM pulses than Pulse Analyzer pulses (see Section 4.2.2), there were many TPM responses that were not detected by the Pulse Analyzer. The reason for this could be a lower threshold setting for the TPM detectors (Ref. 11). However, there were a few pulses that were detected by both the TPM and the Pulse Analyzer, and there were even a few pulses detected by the Pulse Analyzer that were not detected by the TPM. The latter result evidently illustrates the importance of the detector location relative to the discharge site. These TPM pulses indicated a diurnal distribution similar to the distribution obtained from the detector on the 1973 satellite. In Reference 16, it was stated that the occurrence of discharges did not correlate with times of large satellite frame potentials. In fact, on days when large potentials were measured, the TPM usually indicated little activity. On the other hand, Reference 11 states that 80% of the TPM discharges occurred during periods of SSPM charging, that is, presumably large differential voltages on the satellite.

Only one electrical anomaly has been observed on SCATHA due to an air event and that was during a period of only minor SSPM charging. However, a TPM response occurred within one second of the anomaly. This result indicates that the discharge responsible for the anomaly might have been internal, and perhaps inside a cable.

4.2.2 Data from SCATHA Pulse Analyzer

The Pulse Analyzer also registered numerous transient events, most of which were subsequently identified as being caused by normal system electrical operation. Over a period of 447 days, out of 4640 pulses recorded, only 34 pulses on 20 different days could not be definitely associated with normal vehicle commands or ion and electron beam operations (Ref. 12). As indicated in Section 4.2.1, the small number of responses detected by the Pulse Analyzer compared to the TPM could be due to different threshold settings for the instruments.

Pulses that were attributed to discharges were observed on both the external and the internal sensor. It was not known if the Pulse Analyzer external sensor (antenna) was less sensitive to internal system signals than the three internal sensors. This knowledge would be useful for judging how well any external RF sensor could unambiguously differentiate an arc discharge from system-generated noise.

Although the sample size is small (34), these pulses tended to be grouped in the midnight-to-dawn sector, in agreement with most other satellite discharge and anomaly data.

Typical pulses registered 0.08 V to 30 V across 50 Ω, with pulse durations of less than 200 ns and frequency contents from 5 to 32 MHz. Several discharges occurred when the differential potentials on the satellite were going through large changes. The largest chargings and discharges occurred on April 23, 1981.

4.2.3 Data from TPM on 1973 Geosynchronous Satellite

Many discharges were observed by the TPM on this satellite in both geomagnetically quiet and disturbed periods (Ref. 14). During quiet periods, the discharges were predominantly in the local evening to local midnight periods, with count rates as high as 2/min, and 20/hr. During geomagnetically disturbed periods with injection of energetic electrons, count rates as high as 6 to 10/min lasting for close to an hour were observed.

The reason for the relatively large number of observed discharges compared to either the SCATHA TPM or Pulse Analyzer could be because the sensors on the 1973 satellite were mounted amid several OSR panels. It is possible that these panels discharge more or less individually so there are many more discharges around these sensors than on SCATHA. On the other hand, these high count rates might indicate that "conventional" satellites are considerably more prone to discharges than the SCATHA research satellite with its relatively tight Faraday cage and relatively small amount of external dielectrics.

4.2.4 Data from CTS Transient Event Counter

A large number of transient pulses were observed on CTS in a three-month period from February 1976 to April 1976 (Ref. 15). The data have a suspicious appearance because as many as 40 pulses would be observed in a single 1-second period and then often no more discharges would be recorded for hours and even days. The authors of Reference 15 speculate that the large number of discharges in a short period of time could be due to sequential discharging of the large dielectric surfaces on the satellite.

The occurrence of the observed discharges did not exhibit the usual diurnal distribution observed on other satellites. Also, they did not correlate well with the magnetic K index at Anchorage, Alaska, although it was recognized that this K value might not be representative of conditions at the satellite.

Up to the date of Reference 15, no electrical anomalies had been observed on this satellite.

4.3 LABORATORY DISCHARGE EXPERIMENTS

An enormous number of laboratory experiments have been performed on dielectric discharges. Only a small amount of that work, which seems most relevant to the present program, is summarized here.

4.3.1 RF Fields

Attempts to measure the radiated electromagnetic (EM) fields from arc discharges have been made by two separate groups, Stanford Research Institute (SRI) (Refs. 17 and 18) and the Jet Propulsion Laboratory (Ref. 19). The two sets of experiments were very similar in general. The test samples were located inside a dielectric bell jar with the electron gun mounted at the top, and the RF radiation was measured by antennas located outside the bell jar. SRI used simple dipole and loop antennas to measure the radiated fields. The dipole antenna measured the E field normal to the conducting ground plane on which the bell jar was mounted. This sensor was located about 30 cm from the center of the sample. This sensor was the forerunner of the TPM sensor on the 1973 satellite discussed in Section 4.2. JPL used antennas in the far-field region of the radiation (at least 2.5 m from the discharge) with frequency responses from 100 MHz to 8 GHz. The antenna signals were monitored at various frequencies with a bandwidth of 400 MHz.

SRI reported difficulties in their early experiments due to stray electrons from the electron guns accumulating on the inside of the bell jar, whose material composition was not specified. To overcome this problem, they coated the inside of the bell jar with a slightly conductive film which was conductive enough to bleed off the stray charge during the charging period but presumably was not conductive enough to seriously affect the RF radiation as it passed through the walls of the bell jar. JPL did not mention similar difficulties. The reason could be that the bell jar used by JPL was large enough relative to the sample size so that the electron beam could be collimated to miss the walls of the bell jar. Also, it is possible that the acrylic walls of their bell jar were conductive enough to bleed off the stray charge, from secondary and blowoff electrons, without any additional conductive coating. JPL makes a point of the need to perform the experiments in an anechoic chamber to eliminate reflection of the radiated EM signals from the walls of the experiment room.

The SRI signals from the dipole antenna (E field normal to ground plane) were roughly mirror images of the time histories of the return current to the grounded conducting substrate of the sample. This result is reasonable since the normal E field at their sensor location is just the result of the cloud of blowoff electrons which rise from the sample and then produce the return current. Typical response curves lasted for several hundred nanoseconds.

The JPL results showed pulsewidths that were functions of the sampling frequency. At 4000 MHz, a typical pulsewidth was on the order of 100 ns and roughly followed the curve of the replacement current to the grounded substrate. This pulsewidth increased with decrease in the sampling frequency. A curve of sampling frequency versus pulsewidth showed a sharp discontinuity at about 100 ns and 1000 MHz, which the authors of Reference 19 suspected might have been due to the confinement of the blowoff charge by the chamber walls. Thus, the details of such curves should be a function of the chamber size.

Although both of the above sets of experiments demonstrate that RF radiation from arc discharges can be detected, both experiments suffer from the fact that their test samples were grounded. Consequently, when a blowoff occurred, the blowoff electrons had a high propensity to rise to the top of the bell jar, enter the ground side of the electron gun, and return to the substrate via ground paths determined by the gun supports and wiring system. Thus, a spacecharge dipole and a current loop were set up that were dictated more by the experimental setup than by the characteristics of the discharge. Thus, one should use care in trying to apply their specific results to real satellite situations. In particular, the pulsewidths of real spacecraft discharges might be smaller due to spacecharge limiting of the blowoff electrons, and the frequency content of the radiation might be higher. To make the laboratory simulation more representative of an orbiting satellite, a high-impedance ground should be used for the test samples so that the sample will be essentially isolated from ground on the short time scales corresponding to discharges.

4.3.2 Area Scaling

Although arc discharges have many stochastic properties, it has been found experimentally that some important characteristics of discharges, such as total charge released, pulsewidth, peak return current to a grounded substrate, and energy dissipated during the discharge, have reasonably predictable variations with sample area. An early attempt to fit the experimental data available at that time with best-estimate and worst-case empirical functions was made by Al Rosen in Reference 20. As more data became available over a wider range of areas, Balmain (Refs. 5 and 21) was able to fit the data with power-law functions that have plausible physical interpretations. For example, within the uncertainties in the data, reasonable fits are: (1) total charge released (Q) is linear in the sample area, A; (2) pulsewidth (τ) and peak return current (I_p) are proportional to $A^{1/2}$; and (3) power dissipated (P) is proportional to $A^{3/2}$. These results are all consistent with a model in which the whole sample area is discharged during the arc breakdown, and the release of charge proceeds across the sample at approximately a constant velocity, V. Thus, the time scale of the discharge $\tau = L/V = A^{1/2}/V$. The constant of proportionality in these relations is a function of the dielectric material. For mylar, for an area of 10 cm^2, $Q = 2\ \mu C$, $I_p = 30$ A, $\tau = 70$ ns, $P = 0.8\ \mu J$ (Ref. 20).

The results of other investigators, for example, M. Treadaway et al., at JAYCOR, N. Stevens et al. at NASA Lewis, and E. Yadlowsky (Ref. 2), on several dielectric materials are, in general, consistent with Balmain's results although none of these other investigators studied the area dependence in as thorough a manner as Balmain.

4.3.3 Effect of Electron Energy

Most of the early experiments on discharges from dielectric surfaces were performed using monoenergetic electron beams with energies betwen 2 and 35 keV. The discharges from these experiments were characterized by relatively large threshold surface potentials for discharges (sometimes 15 to 25 kV), relatively slow, large-amplitude return currents, and large changes in the surface potentials during a discharge. Since electrical anomalies, which were believed to be due to dielectric discharges, were observed to occur on satellites when their surface potentials were relatively low (considerably less than 10 kV), it was suspected that the laboratory simulations of arc discharges were not replicating what occurs on orbiting spacecraft. A prime candidate for the cause of this difference was the use of the monoenergetic electron beams in the laboratory compared to the distributed spectrum of the space-plasma electrons. Subsequently, a number of investigators (Ref. 22, 23, and 24) performed experiments using two simultaneous monoenergetic beams with various combination of energies or with a distributed-energy beam. Since JAYCOR's work (Ref. 22) in this area is probably the most extensive, and since we are naturally most familiar with those results, the following summary will concentrate primarily on the JAYCOR results.

These JAYCOR experiments revealed that, with a suitable choice of fluxes and energies for 'mid-energy' (≈ 25 keV) and 'low-energy' (≈ 3 to 5 keV) electrons, discharges could be produced on dielectric surfaces when their surface potentials were as low as a few kilovolts, even though their threshold voltages for discharges using monoenergetic electrons were much larger (> 10 kV). The explanation that has been offered for this result is that the mid-energy electrons bury themselves relatively deeply into the surface of the dielectric, and would produce a fairly large surface potential before breakdown down in the absence of the low-energy electrons. However, as the surface potential starts to build up, the energies of the low-energy electrons when they reach the dielectric surface become less than the second crossover point for secondary-electron emission from the dielectric. When this occurs, the flux of secondary electrons emitted by the low-energy electrons is greater than their incident flux, and a positive charge layer builds up on the dielectric surface. Thus, the charge distribution through the sample after irradiation with two electron energies consists of (1) a positive charge in the grounded conducting substrate, (2) a negative charge sheet concentrated near the range of the mid-energy electrons, and (3) a positive charge sheet near the dielectric surface. The corresponding electric fields are positive from the substrate to the negative charge sheet, and then negative from the negative charge sheet to the dielectric surface. With the right set of parameters (material type, electron energies, and dielectric thickness), it is possible to have the integral of the electric fields from the substrate to the dielectric surface (that is, the surface potential) be very small, or even zero, while the internal electric fields are quite large. Thus, since it is electric field and not potential that initiates a discharge, discharges could be initiated by the large electric fields near the substrate while the surface potential is small.

It was found that discharges that occurred during combined-energy irradiations generally had different characteristics than discharges due to monoenergetic electrons. In addition to occurring when the surface potentials were small, the peak return currents for a given sample area were usually smaller, the pulse durations were shorter, and the change in surface potential during the discharge were smaller than for discharges due to the monoenergetic electrons. However, the peak rate of change of the current (dI/dt) was about the same for monoenergetic and combined-energy irradiations. It is reasonable to expect that the RF fields produced by the two types of discharges will also be different for the same sample area. In particular, discharges from the combined-energy irradiations will probably have a lower intensity and a larger high-frequency content. Thus, in choosing a laboratory simulation procedure which hopefully will produce discharges similar to those which occur on actual spacecraft, one approach would be to use a two-energy electron source. However, an alternate, and simpler approach would be to use a smaller sample area with a monoenergetic source, such that the amplitude and duration of the discharge with the small area and monoenergetic source would be comparable to the amplitude and duration of the discharge for a larger sample area with a combined-energy source.

4.3.4 Satellite Noise Measurements

Under a previous program, JAYCOR personnel measured the electromagnetic noise signals at various points on the exterior and interior of an operating Qual model of a satellite where cables were all well shielded. The measurement matrix included 23 B-dot sensors, 30 cable bundle currents, 56 shield currents, 40 pin currents, and currents in two antenna ground straps. All types of sensors exhibited some system noise. The noise signals covered the whole frequency range from periods as long as a few hundred microseconds to as short as 50 ns.

Of particular interest for the present study are (1) the external B-dot sensors, because they should be representative of the radiated RF fields exterior to the satellite produced by system noise, and in case satellite skin currents are chosen as the mechanism for detecting discharges, and (2) the cable bundle currents, which illustrate the problem of trying to discriminate system noise from discharge-induced internal cable signals. The largest noise signal on an external B-dot sensor was less than 0.8 teslas/s while the largest cable bundle current was about 4 mA. It is interesting that some of the measured signals due to system excitations were bipolar, in contrast to the opinion in Reference 16 that system commands on SCATHA would not produce bipolar signals.

For comparison to the skin currents and RF fields produced by an arc discharge, suppose that the B-dot noise has a rise time $t = 50$ ns, comparable to some discharge return currents. Thus the peak skin current density due to the noise would be

$$H = \frac{B}{\mu} = \frac{\dot{B}t}{\mu} \simeq (0.8)(5 \times 10^{-8})/(4\pi \times 10^{-7}) = 0.03 \text{ A/m} \quad .$$

This magnitude of noise should not be a problem when trying to detect a discharge that produces a return current of, say, 2 A and is measured at a distance, say $r = 0.5$ m from the discharge. In that case

$$H(\text{discharge}) \approx \frac{2}{2\pi r} \approx 0.6 \text{ A/m} \quad .$$

For radiated RF fields, one would expect the fields at some distance from the satellite due to the skin currents to be roughly proportional to the skin currents themselves. Thus, again, the radiated RF fields due to noise should be small compared to those due to the arc discharge. However, two cautionary notes should be made. First, for a less well shielded satellite than the one for which the test data were obtained, the internal signals could more easily diffuse to the exterior surface of the satellite and produce relatively larger noise skin currents and radiated RF fields. Also, if another satellite has long booms with unshielded system cables running parallel to them, these cables could also radiate RF noise which might be much larger than the RF fields due to the noise skin currents.

Thus, the question of the magnitude of the background noise in which the arc-detection system will have to operate cannot be answered conclusively at this time and will vary from satellite to satellite.

5. ON-BOARD AND LABORATORY DISCHARGE MEASUREMENT TECHNIQUES

In this section several possible on-board techniques for detecting arc discharges on the exterior of a satellite and for discriminating against system-generated noise are listed along with some of their advantages and disadvantages. In addition, some of the problems in making realistic laboratory measurements, especially for radiated RF fields, are discussed.

5.1 ON-BOARD MEASUREMENT TECHNIQUES

5.1.1 Optical Emission

The emission of light has been observed in the laboratory for many dielectric discharges, and it is probably true that it occurs on all discharges where hot gases are emitted, such as the blowoff that accompanies punchthrough and flashover discharges, although this has not been verified. The main advantage of emitted light as an arc-detection mechanism is that it is unique to arc discharges, since normal system operation should not produce light. In addition, the technology for making such measurements is relatively inexpensive, light weight, and durable. If desired, the specific location of an arc discharge could be determined by triangulation between arrays of detectors. Some of the disadvantages of this system are (1) enough detectors would have to be used so that their fields of view would cover all surfaces on the satellite where discharges might occur; (2) to minimize the number of detectors required, they might have to be mounted on external booms; and (3) the signal-to-noise ratio might be fairly low, especially if the discharging surface were in full sunlight. However, in regard to the latter item, fairly sophisticated (and more expensive) systems have been developed to extract small transient light pulses from a bright background. Also, one could question whether a discharge would ever occur from a dielectric that is in full sunlight, due to photoemission and radiation-induced conductivity caused by the sunlight, so that might not be a practical problem.

5.1.2 RF Radiation

For the discussion in this section, RF radiation is defined to be the radiated EM in the far-field region from the discharge, as opposed to the near-field E field nor the conducting substrate discussed in the next section. Although these two fields a different aspects of the same response, it is convenient for this discussion to mal separation.

The advantages of using RF radiation to detect arc discharges are (1) RF radia known to be emitted from arc discharges; (2) it is possible that this radiation has distinguishing signature characteritstics, within the stochastic nature of discharge (3) this method may be able to detect discharges on the opposite side of a spacecraf the detector, thus minimizing the required number of sensors on a satellite.

One disadvantage of this system is that the sensors may have to be mounted on away from the satellite, and few satellites come equipped with such appendages probably the most serious disadvantage is the fact that normal system ele operations also produce RF radiation from arc discharges. This last conclusion is ba the results from SCATHA, and it is possible that it is unduly pessimistic because choice of sensor types and locations used on SCATHA. Perhaps if one used s mounted on dielectric booms, with self-contained power supplies and fiber optic dat to the satellite, the pickup of system noise by the sensors could be kept below th level for the RF radiation from discharges.

5.1.3 Normal E Fields

The sensors to measure these E fields would be essentially the same as th sensors designed by SRI for the 1973 satellite (Section 4.2), that is, metallic mounted flush to the exterior surface of the satellite dielectric and instrumer measure currents between the plates and spacecraft ground. Such a plate r primarily by capacitive (CV-dot) coupling to the cloud of blowoff electrons wh emitted during the discharge. This near-field electric field is almost quasistatic a often be many times larger than the radiated RF far fields. The maximum detectio of such a sensor from the discharge site would probably be from 0.5 m to 1 m.

The main advantages of such a detection system are (1) it is relatively simple, light weight, and inexpensive; (2) it would be fairly readily adaptable to most satell by comparing responses from different sensors, one should be able to roughly where the discharge occurred, and (4) it is possible that this system would be less s to system-generated noise than a sensor for radiated RF fields. The following is the rationale for the last speculation. The normal E fields due to the blowoff electrons from a discharge are essentially quasistatic and are usually considerably larger than the oscillatory portion of the field which produces the radiated far fields. By contrast, there should be negligible quasistatic fields from the system noise because there is no attendant emitted charge. Therefore, in a case where the radiated far fields due to a discharge and to system noise are comparable in magnitude, the near-field (quasistatic) normal E fields due to the discharge should be much larger than the near-field E fields from the system noise.

One possible disadvantage of such a system would be if too many sensors were required to adequately monitor the complete spacecraft.

5.1.4 Faraday Cups

Since it is known that arc discharges produce blowoff of charge from the dielectric, a system of Faraday cups could be arranged to detect such bursts of current. The cups could be mounted either away from the surface, looking back at it, or on the surface, looking outward, to measure the change in the returning current when a discharge occurs. Cups that look back at the surface should have larger, sharper, and faster response signals than outward-looking cups which have to wait for the blowoff charge to return to the surface. On the other hand, they are more difficult to mount and their coverage area is probably less than for an outward-looking cup.

The major advantage of such a system is that it should uniquely discriminate between discharges and system noise because there would be no pulse of blowoff current due to system electrical noise. Since the Faraday cup could be EM shielded, it should be insensitive to radiated EM fields, in particular those from system noise. The system could also use the time derivative of the current signal to help separate the discharge signals from background currents due to the space plasma. The main disadvantage of such a system might be the number of sensors required to adequately monitor the exterior surface of the satellite which, of course, depends on the presently unknown sensitivity of the sensors.

5.1.5 B-Dot Sensors for Skin Currents

From the standpoint of potentially deleterious effects to a satellite electronics system, the most relevant effect from an arc discharge is probably the resulting replacement skin currents, which then penetrate the Faraday cage of the satellite and couple into the system cables. Thus, if one were primarily interested in detecting potentially damaging discharges, a logical procedure would be to measure skin replacement currents since they are a direct measure of the EM drivers for the system. B-dot sensors could be attached to the exterior surfaces of the satellite at strategic locations around the dielectric regions that are candidate discharge sites. They could be mounted directly over a dielectric surface if the surface has a conducting substrate. In addition to being a fairly direct measurement of the severity of a discharge, other advantages of using skin currents to detect arc discharges are (1) the sensors are relatively light weight, inexpensive and durable; (2) they can be incorporated into most satellites with a minimum of disruption to the rest of the system; (3) by comparing the magnitudes and signs of the currents from different sensors, one should be able to determine the general location of the discharge, if desired; (4) a great deal of laboratory data are already available on discharge-generated skin currents, and (5) similar to the normal E fields (Section 5.1.3), it appears possible that skin currents on the outside of a conducting surface of the spacecraft might be relatively less sensitive to internal system-generated noise than are the radiated RF field, because there is a quasistatic portion of the return currents due to a discharge which does not produce radiation but which will contribute to the reading of the B-dot sensor. Two disadvantages of this system are (1) several sensors would probably be required to monitor all of the potential discharge sites on the satellite, and (2) choosing logical locations and orientations for the sensors requires some knowledge of the flow patterns for the return currents due to discharges.

5.1.6 Witness Wires

A witness wire is defined as any wire that is added to the system specifically to detect EM signals from nearby conductors. The low- and high-impedance wire sensors for the TPM on SCATHA and the wire sensor for the Pulse Analyzer on SCATHA fit this definition. From the SCATHA results, it is clear that witness wires that parallel bundles of system wires will respond to numerous system-generated signals, and thus are poor methods for trying to identify the occurrence of an arc discharge. However, an alternative approach would be to lay the witness wire (or wires) adjacent to the exterior surface of the satellite dielectrics. These wires will respond by CV-dot coupling to sudden changes in the surface potential of the dielectric in the vicinity of the wires, similar to the normal E-field sensors discussed in Section 5.1.3. These wires should have the same advantages as those listed for the E-field sensors, including the possibility that they might be less sensitive to system-generated noise than radiated RF sensors. If anything, an exterior witness wire would probably be easier to add on to a finished satellite than the E-field sensor plates. A possible objection to such wires on the surface of a dielectric is that they might lower the threshold for such discharges, and thus induce discharges when none would normally occur. It should be straightforward to verify or refute this possibility by appropriate laboratory tests. If necessary, one could suspend the wires a few centimeters above the dielectric surface, which should reduce any tendency for the wires to induce discharges in the dielectric and yet not seriously affect their relative sensitivity to discharges versus system noise. Bare wires should probably be used for the witness wires to avoid the possibility of discharge in the dielectric jacket of a cable.

5.1.7 Potential Monitors

The term Potential Monitor could include a variety of sensors. The normal E-field sensors (Section 5.1.3) and the exterior witness wires (Section 5.1.6) respond to changes in local surface potentials and thus are forms of potential monitors. However, they are not the subject of the discussion in this section. The type of potential monitors considered here are the Satellite Surface Potential Monitors (SSPM) used on SCATHA, which respond to the accumulation or depletion of charge in a dielectric or metal, and charged-particle spectra analyzers, which measure the fluxes of incident ions or electrons. The SSPM measure differential voltages between the devices and satellite ground, while shifts in the charged-particle spectra when going from sunlight to eclipse and back again can be used to infer changes in the potential of the spectacraft frame relative to the space plasma. Since both of these potential monitoring systems have relatively slow response times (~ seconds) compared to times of interest for discharges (tens to hundreds of nanoseconds), they would be of little use for trying to detect the occurrence of an arc discharge.

5.2 LABORATORY MEASUREMENT TECHNIQUES

The objective of the laboratory experiments which are contemplated for the present program are (1) to confirm that the candidate phenomenon for detecting arc discharges, for example, emitted light or RF radiation, actually is produced repeatably by discharges, (2) to provide data for estimating the intensity of the phenomenon, perhaps as a function of distance and angle from the discharge, so that required sensitivity of the detection system can be determined, and (3) to measure any characteristics of the phenomenon's signature, such as peak amplitudes and frequency content, which might be useful for discriminating between arc discharges and system noise.

In this section, the possible on-board measurement techniues (Section 5.1) are briefly discussed from the standpoint of the ease or difficulty with which the corresponding measurements can be made in the laboratory and how representative the laboratory data should be of on-board discharges.

If light emission from a discharge occurs, it could be measured easily in the laboratory, including intensity versus time and spectrum data. The measurements could be made inside either a metallic or dielectric chamber and there should be little distortion of the results due to the test chamber. Thus, the measured results should be directly relatable to the arc that created them.

Laboratory RF measurements should be made in a room that is large enough or sufficiently well damped so that reflections from metallic surface other than on the test specimen do not unduly distort the RF waves. As an example, if a discharge has a 50-ns duration, an EM wave will travel 15 m during that time. Thus, to avoid interference between reflected waves from the beginning of the pulse and the emitted waves from the end of the pulse, the test region should have at least a 50-ns clear time. Alternatively, the damping at the boundaries of the test region should be sufficient so that the amplitude of the reflected wave will be much smaller than the radiated wave. Given the desire to keep the vacuum volumes reasonably small to minimize pumping requirements (dimensions on the order of 1 m), it would be very difficult, even if possible, to perform meaningful measurements of radiated RF fields inside a metallic chamber. By the time enough material was put near the walls to damp the outgoing RF waves, there would be little room left for the blowoff electron to execute their normal trajectories. Thus, a dielectric test volume appears necessary. Even so, there are potential problems relating to bleed off of trapped charge from the inside of the chamber walls and distortion of the frequency content of the RF signal due to confinement of the blowoff electrons at late times by the chamber walls, as discussed in Section 4.3.1. Thus, although laboratory measurements of radiated RF fields from discharges have been made, considerable care is required to avoid undue distortion of the radiated signals.

The normal E-field, Faraday cup, B-dot sensor, and witness wire measurements could all be made in a straightforward manner in the laboratory. The simplest experiments would probably be those with the Faraday cup and witness wires because they can be made using relatively small test samples and inside a metallic test chamber because wall reflections would have only minor effects on their signals. B-dot measurements require a test body that is sufficiently large to accommodate the sensors. JAYCOR has previously made measurements of discharge-induced skin currents on a 1-m cylindrical body in a 4 m x 6 m metallic test chamber (Ref. 25). The metallic walls of the chamber undoubtedly had some effect on the measured body currents. However, it is felt that this effect should be fairly small when a high-impedance ground is used for the test object because the main driver for the skin currents is the return of the blowoff electrons to the test body. The trajectories of these electrons should be fairly similar inside a metalic or a dielectric test chamber for an ungrounded test object. The normal E-field measurements could be made with a relatively small test sample. However, depending on how far from the test sample one wants to make the measurements, it might be necessary to have a dielectric test chamber so that the measuring device could be outside the test chamber. One does not want to make a normal E-field measurement too close to the sides of a conducting chamber because the E fields parallel to that surface approach zero at close distances.

Surface potential measurements are made routinely by JAYCOR during discharge experiments, before and after discharges, using Trek probes. However, as discussed in Section 5.1.7, potential measurements are not particularly useful for detecting arc discharge on an orbiting satellite. Hence, these measurements will be used during the test program only for diagnostic purposes.

6. SELECTION OF ARC TYPE AND TENTATIVE PROGRAM PLAN

6.1 ARC TYPE TO BE CONCENTRATED ON

As discussed in Section 2, the large return currents and radiated EM fields produced by arc discharges are believed to be primarily the result of the blowoff electrons which leave the surface of the dielectric during a discharge and generate a large spacecharge dipole moment. Blowoff of electrons is known to accompany both punchthrough and flashover discharges. It is possible that blowoff discharges could occur independent of punchthrough or flashover, but there is no direct evidence that such a discharge has ever been observed. In order to maintain as controlled an experiment as possible, it is felt that the best course is to configure the experiment such that only *one* type of discharge occurs. Preferably, one wants to select the type of discharge which is anticipated to occur most frequently on a spacecraft. For the reasons that are listed below, JAYCOR feels that the present experimental study should concentrate on flashover discharges (i.e., discharges from a dielectric surface to an adjacent conductor) *with their accompanying* blowoff of charge.

Reasons for selecting flashover discharges.

1. Flashover discharges are known to occur.

2. There are numerous locations on most spacecraft where the edges of dielectric sheets are in contact with metal, producing many candidate locations for the initiation of flashover discharges.

3. The threshold potential for the initiation of a flashover discharge is usually less than the threshold potential for initiation of a punchthrough.

4. Hence, it is very likely that many, and perhaps most, exterior discharges on satellites are the flashover type.

5. The blowoff charge that accompanies a flashover can produce significant radiated fields and return currents.

6.2 PROPOSED EXPERIMENTAL PROGRAM FOR MEASUREMENT OF ARC CHARACTERISTICS

The remainder of this section describes JAYCOR's proposed experimental program to measure the characteristics of arc discharges. From discussions with the technical contract monitor the following ground rules have been established for this experimental program.

1. Until such time as it is proven to not be a viable arc characteristic for the purposes of discrimination between surface arcs and spacecraft noise, RF emission will be the arc characteristic that will be concentrated on.

2. For purposes of examining the usefulness of detecting RF emissions to discriminate between surface arcs and spacecraft noise, a single spacecraft material in a fixed geometry will be exposed to monoenergetic electrons to provide a source of arcs.

Briefly summarized, JAYCOR's experimental program will take the following form.

1. Exposure of test samples to monoenergetic 25-keV electrons at fluxes on the order of 1 to 10 nA/cm^2 in an acrylic vacuum chamber.

2. The test samples will be connected to ground by 10^5 to 10^6 Ω.

3. The test sample size will be $\approx$ 10 cm^2.

4. Radiated RF energy densitites will be measured as a function of frequency and distance from the arc source using suitable antennas located outside the vacuum chamber.

The experimental program is discussed in more detail in the following sections.

6.2.1 Test Chamber and Exposure Environment

As discussed in Section 5.2, measurement of radiated RF fields inside a metallic chamber is complicated by reflection of the RF from the chamber wall; therefore, all measurements in this effort will be performed with the sample inside a dielectric vacuum chamber. JAYCOR will construct a cylindrical dielectric vacuum chamber using commerically available plastic pipe 16 inches in diameter. The chamber will be approximately 3 feet long and the electron gun and samples will be mounted on opposite ends of the cylinder. The chamber length has been chosen to be approximately twice its diameter to minimize the influence of the grounded case of the electron gun on the motion of the blowoff charge (see Section 4.3.1).

It is anticipated that all electron exposures will be performed at chamber vacuums lower than 2×10^{-5} torr.

The electron environment will consist of 1 to 10nA/cm^2 of 25-keV electrons. This electron energy is chosen because it is known that most all spacecraft dielectrics that do exhibit discharges will discharge when exposed to 25-keV electrons. Additionally, the majority of data available from laboratory tests of spacecraft dielectric discharges was obtained using monoenergetic 20- to 25-keV electrons. The flux range of 1.0 to 10 nA/cm^2 was chosen because it will result in discharges at a reasonable rate (~ 1 discharge every several minutes). Also most laboratory data available in the open literature was obtained at fluxes in this range.

It is anticipated that the electron beam will be collimated to avoid directly exposing the chamber walls to the electron beam in order to minimize the probability of discharges on the chamber wall. In addition, it is anticipated that the internal chamber walls will be coated with a lossy dielectric which will bleed off any scattered charge collected on the walls, but which will not influence the radiated RF fields.

6.2.2 Sample Grounding

Samples will be connected to ground by a high-impedance (10^5 to 10^6 Ω) resistor string. This resistance is chosen so that the RC time constant associated with this resistance and the capacitance of the sample substrate to ground (50 to 100 pF) will be long compared to the discharge pulsewidth, thus, effectively isolating the sample and its substrate from ground for times on the order of the discharge. It is deemed mandatory to isolate the sample from ground during the discharge in order for the motion of the blowoff charge to more closely resemble that which would occur on a satellite. If the substrate were grounded via a low impedance, the blowoff charge would move along the lines of the electrostatic fields established before the discharging is initiated. The blowoff electrons would flow to the base and walls of the vacuum chamber and the electron gun, following the fields from the sample to the remote outside world. If an entirely dielectric test chamber were used and all grounded metal moved infinitely far away, the blowoff electrons would all flow to the electron gun because its case is necessarily grounded. The source of the radiated RF would then appear to have a strong dipole term associated with the motion of the blowoff charge from the sample to the electron gun (see discussion of JPL experiment in Section 4.3.1). Increasing the resistance of the substrate to ground to 10^5 Ω will make the time constant for the replacement charge to flow from ground to the substrate on the order of 5×10^{-6} seconds ($10^5\ \Omega \times 5 \times 10^{-11}$ f). Thus, if the discharge pulsewidth is on the order of 5×10^{-7} seconds or less, once a small amount of blowoff charge flows to the grounded electron gun, the substrate will rapidly become positively charged. Specifically once 1×10^{-8} coulombs (5×10^3 V/5×10^{-11} f) has flowed from the sample to ground the sample substrate will be charged to a positive 5×10^3 V and, assuming that this is the maximum energy which the blowoff electrons can have, then any blowoff electrons released subsequently will be forced to orbit about the sample and return to the sample substrate. This geometry will be more like a discharging dielectric on an electricly isolated spacecraft than would a sample with a low-impedance ground. Implicit in this argument is the assumption tht the grounding scheme does not influence the dynamics of the discharge process and, therefore, the discharge characteristics, except the motion of the blowoff charge. This assumption has been investigated in previous JAYCOR efforts and found to be valid (Ref. 25).

6.2.3 Sample Material and Size

It is suggested that either SiO_2 (second surface mirrors or solar cell cover slips) or teflon be selected as the test material. SiO_2 has the advantage of being enduring, i.e., the discharge characteristics are not influenced by previous electron tests, and therefore, the issue of aging of the sample during a test sequence is hopefully avoided. Teflon is desirable since recent measurements by JAYCOR indicate that teflon often emits a plasma when it discharges (SiO_2 apparently does not) which will probably add a high frequency component to the radiated RF signature. It is believed that such plasma ejection is common to most discharging plastics.

It is suggested that the size of the samples be selected to produce discharge pulsewidths similar to those reported for the SCATHA flight data which were on the order of 10 to 25 ns. Using Balmain's scaling laws (Ref. 5) which indicate that the pulsewidth of discharges for a given material scales as the square root of the area of the sample and data from Treadaway (Ref. 25) and Coakley (Ref. 23) which indicates that the pulsewidths for discharges on 6,500-cm^2 and 360-cm^2 diameter SiO_2 samples were 1 µs and 350 ns, respectively, the sample size should be from 2 to 4 cm^2. This approach must be balanced against the decrease of the energy in the discharge (and thus the radiated energy) as the sample size is decreased. A 10-cm^2 sample area is suggested since this is about a factor of three smaller area than used by Leung and Plamp (Ref. 19) and thus should result in measurable radiated RF signals and should increase the pulsewidth to only 40 to 60 ns from the desired maximum of 25 ns.

6.2.4 RF Measurements

Although the specific detectors (antenna, etc.) and amplifiers have not been identified at this time, the quantities to be measured can be discussed. Since the application of the data from the laboratory measurements of RF emission is ultimately toward developing a discrimination technique between satellite surface arcs and spacecraft operational noise, one must necessarily have some idea of the possible discrimination methods in order to determine what to measure. Generally the types of discrimination techniques are based upon discrimination via

1. Amplitude of RF from arcs vs. noise
2. Frequency content of RF vs. noise in a discrete frequency bin
3. Relative amplitudes at two or more frequencies
4. Identifying the location of the radiation (outside vs. inside) by the use of multiple sensors.

Since the most promising technique has not been identified we must necessarily gather data that will allow us to distinguish the relative merits of these techniques. To accomplish this task we suggest that measurements be made of the time history and power of the radiated RF as a function of frequency and distance from the arc to the detectors. This will be accomplished by placing antennas (the optimum antennas to be used have yet to be identified) at various distances from the arc source and measuring the received power as a function of time. The antennas will be coupled to bandpass filters and measurements will be made in a number of frequency bins. Based on the work of Leung and Plamp it may be desirable to include frequencies as high as several gigahertz. The lower limit of the frequency regime should be as low as the frequency of the return current envelope which we have forced by sample size and material selection to be on the order of 50 nsec (7 MHz) assuming that suitable detectors can be fabricated. Several additional factors that must be considered that were not considered in previous measurements of this ilk are (1) the spatial nonuniformity of the RF emission, (2) the discharge to discharge variations, and (3) polarization effects of the RF characteristics. The first item will be addressed by placing identical sensors at 90^{o} and/or 180^{o} from one another (in the plane of the sample as well as out of the plane of the sample) for simultaneous measurements within the same frequency bands. The issue of discharge to discharge repeatability will impact on our ability to correlate measurements within one frequency bin to those in another frequency bin. To address this issue, measurements will be made simultaneously in two or more frequency bins using either the same antenna or co-located antennas. Variations from discharge to discharge in the relative signals within the two frequency bins will provide data on the variability of these signals which may be an important factor in evaluating a discrimination technique, particularly one that relies on discrimination by sampling several discrete frequency regimes, i.e., the power spectrum of the emitted RF.

Polarization effects are significant in that the signal recorded from an antenna will be dependent on the relative orientations of the polarization of the emitted RF and the antenna (this is particularly true of a microwave antenna such as that used by Leung and Plamp). The polarization of the emitted RF is obviously indicative of the microscopics of the motion of the charge in the surface arc (and the blowoff charge) and thus information on the polarization may yield information regarding the details of the arc. To investigate this effect antenna will be colocated and oriented at 90° with respect to one another and the outputs recorded separately.

In the far field the electric and magnetic fields of the radiated RF are related by the impedance of free space. Typically the far field is defined as being at a distance greater than or equal to ten times the wavelength away from the source. For 1 gigahertz, 500 megahertz and 7 megahertz, this corresponds to far-field distances of 300, 600 and 4×10^{4} cm (1400 feet) respectively. Obviously for the 7 megahertz component of the radiated fields we will not make far-field measurements and probably will not be in the far field (due to laboratory size constraints) except for frequency in excess of 500 megahertz. It is interesting to note that the measurements described by Nanevicz and Leung and Plamp were all in the near field. The electric and magnetic fields in the near-field region are not related simply by the impedance of free space.

It is anticipated that the results of these measurements will be used as a guide for future measurements. The future tests may take the nature of additional electron tests on plasma samples or on small scale cans or may include the use of spark gaps as surface arc mimics with associated measurements of inside versus outside signal amplitudes on a 3-ft diameter semi complex model satellite. The latter measurements may be useful if the results of the initial measurement of radiated RF indicate a frequency spectrum that has components which cannot effectively radiate through apertures representative of those encountered on spacecraft. One can then imagine that a suitable detection technique would involve the measurement of radiated RF in a high and a low frequency band on the outside of the spacecraft. Such measurements could be made using a single sensor with two band pass filters and two channels of a SRI-type TPM. The relative magnitudes of the detected RF in the two frequency bands for a surface arc would be different from those for an internal arc since the low-frequency component would not leak through any aperture as effectively as the high-frequency component. Likewise it would be unlikely that any spacecraft electrical noise would have the same relative amplitudes within the two frequency bands.

Of course the specific direction of additional measurements will be defined once the results of the initial measurements are available and will be defined in coordination with the technical contract monitor.

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APPENDIX A.

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The following is a bibliography of the major information sources that have been found on arc discharges. For the proceedings of the three Spacecraft Charging Conferences, specific papers of primary interest are called out. There are other large bodies of information in the open literature on the space environment and the charging up portion of arc discharges. Only a few of the these articles that appear most relevant to the present study are specifically noted. However, the interested reader can locate many related articles in the proceeding of the Spacecraft Charging Conferences and in the references in the listed papers.

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